When Renewable Energy Meets LoRa: A Feasibility Analysis on Cable-less Deployments

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***Abstract*—In recent years, Low Power-Wide Area Networks gained momentum thanks to their inherent capabilities to support Internet of Things services with broad geographical coverage. Among them, the Long Range Wide Area Network standard, recently promoted by the $LoRa^{TM}$ Alliance, is emerging as one of the most promising solution capable to provide a radio coverage up to tens of kilometers with very low data rates, while working in the unlicensed sub-GHz band. This paper focuses on Long Range Wide Area Networks and sheds some light on the feasibility of fully cable-less Internet of Things deployments, where dual-radio gateways are fed by a photovoltaic plant and equipped with a wireless backhaul. As a first step, the power needs of a dual-radio gateway, serving a mix of realistic Machine-to-Machine applications and leveraging different combinations of front-end chipsets and backhaul wireless technologies, are investigated. Then, the achieved results are properly employed to size the photovoltaic plant, as well as to estimate its installation costs and land acquisition. Finally, cost-saving and carbon footprints analysis is presented to demonstrate the socio-economic benefits arising out of these cable-less deployments for Long Range Wide Area Networks. The conducted study clearly exhibits that network operators can achieve their break-even point during the early stages after the deployment, while adopting environment-friendly approaches because of carbon emission savings achieved by renewable energy.**

***Index Terms*—Internet of Things, LoRaWAN, renewable energy, cable-less LoRa gateways, LoRa feasibility analysis.**

I. INTRODUCTION

Long Range Wide Area Network (LoRaWAN) recently got a significant attention by the research community, industry, and several network operators because of its capability to match coverage, scalability, and energy efficiency requirements of Internet of Things (IoT) deployments [1]- [3]. It integrates the Long Range (LoRa) technology at the Physical (PHY) layer, provides specifications for both Media Access Control (MAC) and network layers, and defines the four key components of the overall architecture, that are end-nodes, gateways, cloud/network servers, and remote applications [4].

LoRaWAN is still undergoing an evolutionary phase: current activities are investigating several challenges related to energy optimization and harvesting in long range networks, different modeling techniques for LoRa, as well as evaluating the performance and the limitations of the LoRa technology (see Section II-C for more details). As worldwide recognized, however, conventional LoRaWAN gateways are assumed to have a wired (IP based) connectivity mechanism with the backhaul network. Certainly, a wired backhaul provides a very high capacity. But, it also incurs wiring costs, hinders on-the-fly deployments, and limits network expansion. To circumvent these limitations, the work presented herein proposes a feasibility study that analyzes pros and cons of fully cable-less LoRaWAN gateways, fed by Renewable Energy Sources (RES), and leveraging a wireless backhaul to interact with cloud/network servers and remote applications.

In more details, the following fourfold contributions are achieved. First, the power demand of a cable-less LoRaWAN gateway equipped with a dual radio interface is estimated by taking into account the throughput achievable within LoRaWAN front-end, the energy consumptions of real LoRaWAN gateways currently available in the marketplace, and energy models theorized for different wireless backhaul technologies. Second, power and storage ratings of a Photovoltaic (PV) plant capable to feed a cable-less LoRaWAN gateway, as well as the land occupation of the plant itself, are calculated by properly considering a realistic deployment in the south of Italy. Third, Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) for both conventional grid-powered and proposed cable-less LoRaWAN gateways are also estimated and a detailed cost saving is presented to highlight the economic benefits for the network operators (i.e., network operators can achieve their break-even soon after the deployment of the proposed cable-less architecture). Lastly, an analysis on the carbon emission is presented to demonstrate how the proposed model is capable to guarantee an annual carbon emission savings up to 56kg per gateway, when compared against conventional grid-powered infrastructures. The proposed LoRaWAN architecture emerges as a flexible, cost-effective, and environment-friendly solution. It is an extremely encouraging factor that makes it economically viable for the network operators to consider this approach in terms of return on investment.

The rest of this article is organized as follows: background of LoRa technology is discussed in Section II. Section III presents the envisaged system model using LoRaWAN at the front-end and different wireless technologies at the backhaul.

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Section IV estimates the overall power consumption of the cable-less LoRaWAN gateway. The size of a PV plant for the proposed cable-less LoRa gateway is discussed in Section V, while a detailed feasibility analysis comprising cost and socio-economic benefits is presented in Section VI. Finally, concluding remarks and future research activities are presented in Section VII.

II. ESSENTIAL BACKGROUND AND RELATED WORKS

LoRa is emerging as a key technology enabler for low power and long range communications [3]. At the beginning, it was particularly intended for low data rate applications developed by a French company Cycleo, later acquired by Semtech. Consequently, it was adopted by the LoRaWAN network architecture, i.e., an open-source standard built on the top of the proprietary LoRa physical layer [4]. At the time of this writing, LoRaWAN is a step ahead among other proprietary LP-WAN competitors, right from the inception, and now it is ready to support several use-cases of future IoT services in smart cities, smart home and buildings, smart environment, smart metering, smart agriculture, and other domains [5].

A. LoRaWAN architecture and node's capabilities

The baseline LoRaWAN architecture follows a simple star-of-stars topological structure. A bulk of LoRa end-nodes are connected a remote LoRa cloud/network server through one or more LoRa gateways. A LoRa end-node may integrate any kind of sensor (e.g., temperature, motion, smoke) belonging to the IoT physical world and it is able to transmit data to LoRa gateways by using the Industrial, Scientific, and Medical (ISM) band. Whereas a LoRa gateway is a simple relay device capable of listening on multiple LoRa channels and forward the uplink traffic received from end-nodes to the remote LoRa cloud/network server. LoRa cloud/network server is assumed to be responsible for analyzing and responding to the requests in an appropriate manner after processing. The end-users interact with the system using several LoRa applications that are connected to the LoRa cloud/network server via a simple web interface. Finally, applications can collect their required information by accessing the LoRa server whenever needed. Users can also control the operation of end-nodes by issuing their commands to the end-nodes as per their rights [4].

End-nodes can be classified into three different categories [6]. End-nodes belonging to class A offer a limited reception window (with maximum two receive slots of almost 1-second duration) and are more suited for uplink data-intensive applications. They embraces the default functionality that every end-node belonging to the LoRaWAN network architecture should always possess. Class B devices are capable of opening an extra scheduled receive window for the downlink. Contrarily, class C end-nodes have an always active reception window at the cost of very short battery time causing constant grid connectivity.

B. Physical transmission and channel access in LoRaWAN

End-nodes and the nearby gateways exchange data through the front-end communication interface, by employing a single-hop and bi-directional (although half-duplex) LoRaWAN communication protocol. Unlike conventional cellular networks, uplink communication is mostly dominant in this kind of networks.

At the physical layer, LoRa supports the choice of a flexible number of channels, bandwidth, spreading factor, and code rate to be used for data transmission [7]. The number of channels and their available bandwidth options depend on the target region and the choice of a LoRa vendor (i.e., up to 10 channels in Europe and 64 channels in North America).

The spreading factor, SF, is defined as the logarithmic ratio between symbol rate Rs and chip rate Rc, as reported in Eq. (1).

$$SF = log_2 \frac{Rc}{Rs}. \tag{1}$$

Typical values span from 7 to 12 and the choice of a given spreading factor provides a trade-off between the data rate and communication range. At the same time, SF allows achieving concurrent communications between several end-nodes and a gateway, without incurring to interference phenomena. This is true even if the same channel is selected. The code rate is the ratio of the forward error correction with the original data stream to be encapsulated. It is chosen among the range of 4/5 to 4/8. To optimize the lifetime of end-node batteries and network capacity, LoRaWAN networks may employ an Adaptive Data Rate scheme if explicitly requested by the end-node. Alternatively, end-nodes are free to choose any available channel at any given time and available data rate as their default, by means of a pseudo-random channel hopping. To conclude, the achievable physical data rate lies between 0.3kbps to 50kbps, depending upon the combination of the frequency channel, spreading factor, code rate and, chosen modulation technique.

At each transmission attempt, the end-node must comply with the constraints imposed by local regulations regarding the duty-cycle, d, expressed as the percentage of the time during which a channel can be allowed to occupy and consequently, end-node may transmit. Therefore, in addition to the PHY/MAC design of LoRaWAN, the performance of these networks is also affected by restrictions of the duty-cycle [7]. For example, 1% of duty-cycle (which is typically imposed in Europe) implies a maximum transmission time of 36 seconds/hour per end-node. Let Ta and T_s be the time required to submit a packet in a sub-band for transmission (also named as Time on Air) and the time during which the channel is not available for transmission, respectively. In case the channel is not available, the end-node must wait for a time interval equal to T_s before scheduling the next transmission. According to [7], it emerges that:

$$T_s = T_a \left(\frac{1}{d} - 1 \right). \tag{2}$$

Hence, the maximum number of packets that a node can transmit in an hour, N_{max}, is equal to :

$$N_{max} = \frac{60 \cdot 60}{T_a + T_s} = \frac{3600}{T_a} d. \tag{3}$$

Once the channel is selected by end-nodes with an appro-

TABLE I
A COMPARISON OF PROPOSED CABLE-LESS LORA GATEWAY APPROACH WITH CURRENTLY AVAILABLE LITERATURE

Literature	**Energy harvesting/optimization**	**Modeling**	**Performance evaluation/limitations**	**Cable-less LoRa gateways**
[8]- [10]	✓	x	x	x
[11], [12]	x	x	✓	x
[13], [14]	x	✓	✓	x
[15], [16]	x	x	✓	x
Proposed approach	It extends any other solutions by offering cable-less deployments.			✓

priate SF, the access to the medium is governed by the well-known ALOHA protocol, where a pseudo-random channel hopping strategy uniformly distributes the number of devices over the available channels and concurrent transmissions from two end-nodes only encounter a collision if they both select the same SF while transmitting at the same channel.

C. *Current research trends*

Several works [8]- [16] recently addressed different issues related to the core LoRaWAN mechanism (discussed throughout this section). In summary, the broad topics of interest include (1) energy optimization and harvesting in long range networks, (2) different modeling techniques for LoRa and, (3) evaluation of several performance metrics (like capacity, scalability, and radio coverage).

In more details, a multi-sensing platform has been proposed by [8] that strives to achieve energy sustainability by employing multiple techniques (i.e. energy harvesting and ultra low-power wake-up radio) for the LoRa based end-devices when deployed in the continuous listening scenarios. Similarly, [9] come up with a circuit capable to handle and switch between multiple harvesting techniques to feed a LoRa end-device to claim improved device autonomy and Quality of Service. Another similar approach has been presented by [10] introducing the floating device integrating energy harvesting and communication system together to achieve longer battery life of LoRa nodes especially in the very long-range communication. A stochastic geometry framework on the performance and scalability of single gateway based LoRa network is presented in [11] which argues about the exponential drop of coverage probability with growing number of end-nodes. An experimental analysis on the coverage of LoRaWAN is conducted in [13]. The authors use maximum transmit power and SF to evidently observe the communication range as 15 km and 30 km for the test-beds located on the ground and water, respectively. The authors also present the channel attenuation model based on the experimental data set to estimate the path loss. The same authors have drawn performance metrics for LoRaWAN end-nodes in [12] and illustrate that a single LoRaWAN cell can support several millions of end-nodes. They conclude that the capacity of uplink LoRaWAN channel is highly dependent on the distance from the gateway. Similarly, the indoor and outdoor performance of LoRaWAN physical layer has been analyzed in [15] which demonstrates that LoRaWAN may be a reliable link for future remote sensing applications. [14] propose a Markov chain model for on-the-air activation (network join procedure) and derive expected delay and energy requirement to join an existing network. Lastly, a survey [16] on the limitations of LoRaWAN with massive Machine-to-Machine (M2M) traffic declares channel access as the most crucial component and reveals that an accurate interference-aware performance analysis is needed in these conditions.

To the best of our knowledge, all the proposals available in the literature so far (summarized in Table I), leverage a wired LoRaWAN backhaul with grid-powered gateway solutions. On the contrary, this work deeply investigates the possibility to deploy cable-less LoRaWAN gateways, under different settings. Moreover, the proposed solution can be easily applied together any other approaches proposed in the literature, while extending their capabilities towards cable-less deployments.

III. SYSTEM MODEL

The LoRaWAN system envisaged in this contribution pursues a completely cable-less architecture, as illustrated in Figure 1. Both the front-end and the backhaul communication links are wireless: the LoRa technology is used for the front-end and different wireless technologies may be used to connect the LoRAWAN gateway to the rest of the network. In addition, LoRaWAN gateways are fed by some RES. Thus, energy sustainability represents the key challenge to face in the proposed architecture.

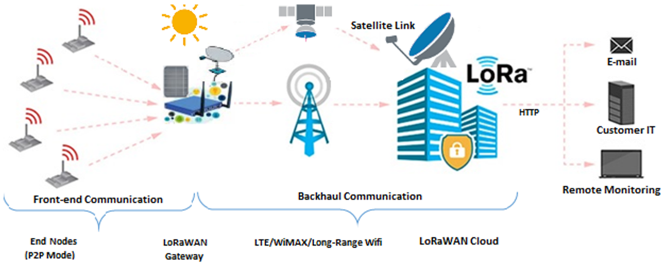

Fig. 1. The proposed energy harvesting cable-less LoRaWAN architecture.

Each kind of RES has its own pros and cons, depending on the type of application and environmental constraints. Nevertheless, employing the photovoltaic plant might be a suitable idea to power up the gateways. Such an approach has already been chosen for other technologies in cellular architectures where low power base stations in micro and femtocells are fed by solar plants [17]. This way, in fact, it is possible to reach out a suitable trade-off between the power requirements of the LoRa gateway and the harvesting capacity of the PV plant. Accordingly, the present contribution focuses on cable-less LoRaWAN gateways, equipped with PV plants that are capable of satisfying the power demand of both the front-end communication interface (i.e., the LoRa technology) and the chosen backhaul wireless technologies.

As demonstrated in [17], the resulting energy harvesting architecture would be able to provide flexible architecture, affordable CAPEX, reduced OPEX, and minimized carbon emission. This kind of solution is particularly useful in the use-cases where: (i) the direct grid connectivity is not feasible because of odd installation spot; (ii) the grid connectivity limits the performance (e.g. in terms of achieving optimum radio coverage) of LoRa gateways; and/or (iii) the service providers are intended to cut-down the operating costs. These benefits would not only enable the existing private and public LoRaWAN infrastructures to upgrade themselves, but it would also be able to support new LoRaWAN business use-cases, including:

- **Low power network operations:** one of the unique characteristics of LoRaWAN networks is their operations in the license-free spectrum with certain duty-cycle and maximum-power constraints. The proposed architecture might help network operators to effectively install and operate their gateways while functioning in low power conditions.
- **Coverage and capacity enhancements:** by employing cable-less gateways to the existing LoRaWAN networks, it would enable network operators to quickly initiate network expansion process yielding improved coverage and capacity of the network in a cost-effective way.
- **Rapid expansion:** the notion of cable-less gateway (employing a wireless backhaul to connect to the core network) would enable existing and new network operators to flexibly install their gateways with minimal costs in urgent situations. It may particularly be feasible in rural areas and developing countries.
- **Lower deployment costs and time to market:** grabbing the possibility of multi-backhaul capabilities, it would be handy for service providers to come up with the speedy deployment of LoRa networks by utilizing many of the existing wireless technologies already deployed in the potential areas. This is far better than the installation from the scratch.

A. An overview of the different stages of the procedure

Figure 2 provides an overview of the various stages involved towards accomplishing a cable-less LoRa gateway. As an initial step, application throughput is calculated for a range of M2M applications that serves an input to further compute the optimal number of end-nodes to be served by a single LoRa gateway. The power consumption is then evaluated as a second step taking into account the consideration of different LoRa vendors and different backhaul technologies based on the aggregated traffic calculated in step 1. Once the power consumption is known for different combinations of front-end and backhaul options, we can move towards the sizing phase in step 3 where power rating of a PV plant is calculated. As a step 4, we evaluate the storage requirements to support uninterrupted operation also in the bad weather conditions when the PV plant generation is absent. The appropriate storage ratings are calculated in step 5 to accommodate the ample amount of energy required to support sustainable gateway operation. Lastly, cost and carbon footprints savings calculations are executed as step 6 where a detailed analysis is presented for the network operators with respect to CAPEX, OPEX and break-even points achievable through different front-end and backhaul combinations.

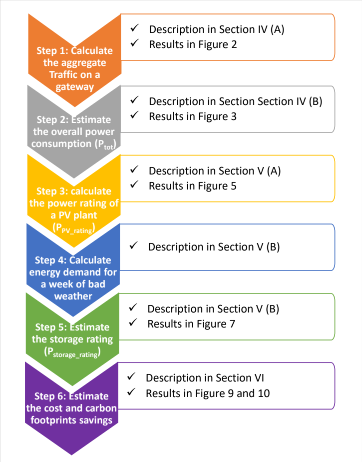

Fig. 2. Big picture of different stages of the adopted methodology.

B. Assumptions and constraints

There are a number of assumptions related to each phase of the procedure presented in Figure 2. As a part of step 1, a range of M2M applications are assumed based on the low, middle and high throughput intensive applications to evaluate the extreme traffic requirement and to justify the choice of backhaul technology for various IoT use-cases. Secondly, the evaluation of number of optimal end-nodes served by a single LoRa gateway assumes a pure aloha based channel access, which only considers 3 and 6 LoRa channel configurations. Step 2 assumes an average power consumption reading for all the combinations of front-end and backhaul technologies. While evaluating front-end power consumptions, a slight variation in the consumption reading due to different hardware chipset is negligible. Moreover, different assumptions related to the power consumption of each backhaul technology are presented in detail in Section IV-B. Step 3 presumes weather conditions of a specific region while calculating the power ratings for PV plants. The related outcomes are used when evaluating power requirements for a weak of bad weather conditions in step 4. Hence, the number of days with bad weather conditions would vary with respect to certain regions. The lithium-ion battery of 90% efficiency and 4h discharge time is assumed while evaluating the storage rating on stage 5. Furthermore, step 6 assumes 10 years of lifetime for cable-less LoRa architecture. It further assumes to neglect the costs

Algorithm 1 The pseudo-code for the adopted procedure

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procedure DIFFERENT STAGES OF THE PROCEDURE
Step 1: Calculate the aggregate Traffic on a gateway
    $\Psi \leftarrow$ available spreading factors from 7 to 12
    $n_j \leftarrow$ max no. of end-nodes supported by a SF
    $c \leftarrow$ the number of LoRa channels
        Calculate optimal number of end-nodes, $O_n$ using Eq. (4)
    $S_{app} \leftarrow$ average packet size
    $R_{app} \leftarrow$ average tranmission rate
        Using $O_n$, calculate the achievable throughput,$T_{app}$ using Eq. (5)
Step 2: Estimate the overall power consumption, $P_{tot}$
    $P_{FE} \leftarrow$ avg. power consumption of LoRa front-end
    $P_{BH} \leftarrow$ avg. power consumption of backhaul tech.
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate total power consumption,$P_{tot}$ using Eq. (6)
        end for
    end for
Step 3: Calculate the power rating of a PV plant, $P_{PV\_rating}$
$H_{ins} \leftarrow$ average insolation period
$H_{year} \leftarrow$ total number of hours in a year
$P_{tot} \leftarrow$ total power consumption calculated in step 2
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate power rating, $P_{PV\_rating}$ for all $P_{tot}$ in Step 2 using Eq. (8)
        end for
    end for
Step 4: Calculate energy demand for a weak of bad weather conditions
$N_{BW} \leftarrow$ the number of days of bad weather
Energy demand during bad weather conditions, $E_{BW} = N_{BW} \cdot 24h \cdot P_{tot}$
Step 5: Estimate the storage rating, $P_{storage\_rating}$
$\eta_{batt.} \leftarrow$ percentage of battery efficiency
$T_{discharge} \leftarrow$ battery discharge time
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate storage rating, $P_{storage\_rating}$ for all $P_{tot}$ in Step 2 using Eq. (9)
        end for
    end for
Step 6: Estimate the cost and carbon footprints savings
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Cost Saving (CS) is calculated as a function of $C^{Grid}_{CAPEX}$ using equation (10) and Carbon footprint saving is evaluated using Eq. (12)
        end for
    end for
end procedure
```

involved in the land acquisition while calculating the cost savings for network operators.

The proposed work is carried out considering the deployments in the south of Italy based on the local weather conditions. Therefore, geographical location may be seen as one of the main constraints where the proposed approach needs to be adapted as the results may undergo abrupt variations in different regions because of the variable insolation period, and number of days with precipitation, of various regions (See Section V for the details).

IV. ESTIMATING THE POWER CONSUMPTION

A. Aggregate Traffic Model for M2M Applications

The aggregate traffic that a LoRaWAN gateway has to manage is estimated by taking into account typical M2M applications (like Roadway Signs, Traffic Lights/Sensors, House Appliances, Credit Machine in a shop, and Home Security [12], [18]). It essentially serves the twofold purpose. First, identifying an appropriate backhaul technology for LoRaWAN network architecture that supports the aggregate traffic. Second, evaluating the energy consumption of proposed cable-less gateway in the presence of a wireless backhaul technology.

The LoRaWAN cell is defined as the portion of the LoRaWAN network handled by a single gateway. Let Ψ be the number of available spreading factors, chosen from 7 to 12 as already discussed in Section II. The number of end-nodes that can successfully be served in a LoRaWAN cell depends on (i) the maximum number of end-nodes supported by every single spreading factor, n_j, with $0 \leq j < \Psi$, (ii) the number of channels, c, and the real number of nodes whose transmissions do not collide over the shared channel. Now, considering the pure ALOHA as the baseline channel access mechanism, it can be assumed that 1/2e of the end-nodes in perfect synchronization can be supported optimally in collision situations within a LoRaWAN cell [12].

Thus, the optimal number of end-nodes supported in a LoRaWAN cell, O_n, can be expressed as [12]:

$$O_n = \frac{1}{2e}\, c \sum_{j=0}^{\Psi} n_j \tag{4}$$

In addition, for every single M2M application listed above, the upper bound value of the achievable throughput, T_{app}, can be computed as:

$$T_{app} = \frac{S_{app}}{R_{app}}\, 0_n = \frac{S_{app}}{R_{app}} \frac{1}{2e}\, c \sum_{j=0}^{\Psi} n_j, \tag{5}$$

where S_{app} and R_{app} are the average packet size and the average transmission rate of a given application, respectively.

Figure 3 shows the upper bound value of the achievable throughput against various M2M application scenarios. It is computed by considering configurations with three and six LoRa channels of 125kHz each. Of course, a higher number of channels can accommodate more number of optimal end-devices and, hence, yielding higher throughput. Moreover, by observing the results, it is possible to remark that, being a low data rate technology, LoRaWAN can still support a bulk of application scenarios for IoT. But, it is pertinent to note that the throughput requirement for most of the M2M application scenarios in LoRaWAN does not go beyond few kilobits per second as shown in Figure 3.

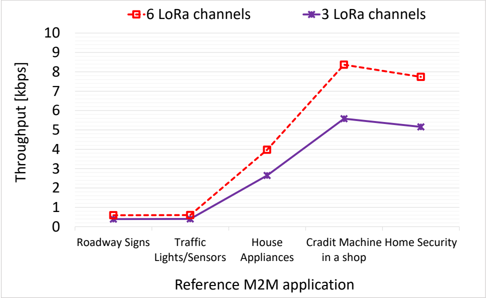

Fig. 3. LoRaWAN throughput against various M2M application scenarios.

B. *Power Consumptions for a cable-less LoRaWAN gateway*

The overall power consumption of a cable-less LoRaWAN gateway in dual radio mode, P_{tot}, would be the combination of the power requirements due to front-end, i.e., P_{FE}, and backhaul communications, i.e., P_{BH}:

$$P_{tot} = P_{FE} + P_{BH}. \tag{6}$$

Of course, P_{FE} refers to the specific implementation of the LoRa technology. P_{BH}, instead, depends on the wireless technology adopted for the backhaul. Here, It is significant to note that the energy evaluation drawn in this section for both front-end and backhual combinations, represents the overall energy demands to make the devices operational.

Front-end power consumption, P_{FE}

A lot of companies (i.e., Multitech, Microchip, Libelium, Loriot, and many others) are providing end-to-end LoRa business solutions for catering the needs of many different enterprises. Their solution kits include LoRa cloud/network servers, gateways and, end-nodes (intended for LoRaWAN applications) with license covering full/partial network support for a contract period. Some of the companies are core manufacturers; while others outsource most of the components for their clients. The average power consumption readings for front-end LoRa communication chipset, along with the lower and upper energy bounds of different LoRa gateways available in the market, are mentioned in Table II. The overall power consumption values are calculated based on the information provided within the data sheets of different LoRa gateway vendors[1].

TABLE II
POWER CONSUMPTION OF FRONT-END LORAWAN GATEWAYS OFFERED BY DIFFERENT VENDORS

LoRaWAN Gateway Vendors	P_{FE} **(W)** Min.	Max.	Average
Multitech Conduit	5.69	6.68	**6.18**
Embit EMB-GW1301	5	7.5	**6.25**
Kerlink Wirenet 868	3	15	**9**
LoRANK 8	N/A	N/A	**10**
Links-lab LoRa	10	13	**11.5**
Lorrier LR2	N/A	N/A	**12.44**

Backhaul power consumption, P_{BH}

For the backhaul, four important and most widely used wireless technologies are considered in this study. They can be employed in combination with LoRaWAN networks where the traffic demands are not higher even in peak traffic scenarios, while offering good performance in terms of coverage, network capacity, and scalability. The selected backhaul technologies that satisfy these requirements include Long Term Evolution (LTE), Worldwide Interoperability for Microwave Access (WiMAX), satellite, and Long-Range WiFi. The energy consumption related to each of these technologies is evaluated by considering a set of assumptions to make its calculation straightforward. It involves many complexities when estimating the partial energy consumption for a single network component while ignoring others that may cause slight variations in value reading. Similarly, power consumption is highly dependent on the underlying hardware chipset and may vary from vendor to vendor.

LTE has already been recognized as a widespread commercialized standard for cellular networks. It is capable to support reasonable bandwidth with fair radio coverage; good enough to be served as backhaul for LoRaWAN networks. In LTE, the amount of power consumed by a mobile terminal is influenced by several components, like base power (minimum power required when the mobile terminal is switched on with modem and transceiver both off), transceiver, modem, and microprocessor consumption with a transceiver variability of ± 0.1W. Transceiver and microprocessor introduce the major power consumption when compared to the other components. Also, the energy demand of the transceiver may introduce slight changes when the physical data rate increases. Nevertheless, with reference to the aggregate traffic load available within a LoRaWAN cell, it is possible to safely set the power consumption of an LTE mobile terminal to an upper bound value equal to $5.10W$. Specifically, this value is obtained by subtracting the amount of power needed for screen illumination from the summation of power needed by all other components such as modem, transceiver, and microprocessor [19].

WiMAX has proven itself as a prominent broadband wide area solution for wireless networks. It exploits the advantages of Orthogonal Frequency Division Multiplexing (OFDM) technique yielding long coverage with high data rate support. WiMAX has already been recognized as the strong backhaul

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[1] Multitech Conduit: http://www.multitech.net/developer/products/conduit/mtcdt-power-draw
Embit EMB-Gateway1301: http://www.embit.eu/wp-content/uploads/EMB-GW1301_20160718.pdf
Kerlink Wirenet 868: http://www.kerlink.fr/en/products/lora-iot-station-2/wirnet-station-868
LoRANK 8: https://webshop.ideetron.nl/LORANK-8
Links-lab LoRa: http://www1.futureelectronics.com/doc/LINK%20LABS/LL-BST-8.pdf
Lorrier LR2: https://lorrier.com

technology with multiple front-end access infrastructures. The Customer Premises Equipment (or simply named WiMAX modem) is responsible for relaying the user traffic through the backhaul network in WiMAX. Alvarion BreezeMAX USB 200 Zyxel MAX-200M1 device is considered to estimate the power consumption of Customer Premises Equipment. It is recorded as $5W$ approximately for the mentioned Customer Premises Equipment model while neglecting slight variations possible due to different hardware chipset [20].

Satellite Networks might be another significant candidate that successfully conforms to the requirements drawn by front-end LoRaWAN network. It is capable to provide low data rate support on very long distances with the delays compromisable for many M2M applications. In fact, it may be a promising approach for LoRaWAN to employ satellite networks as a backhaul for covering such a long distance that does not seem achievable with conventional LoRaWAN networks especially in urban areas. European Telecommunications Standards Institute (ETSI) recently published a comprehensive report, i.e., [21], on evaluating the power needs of various components of a satellite broadband network. Specifically, the power consumed by satellite terminal can be evaluated as:

$$P_{BH}^{sat} = T_{full}\, P_{full} + T_{standby}\, P_{standby}, \tag{7}$$

where $T_{full}, T_{standby}, P_{full}$, and $P_{standby}$ are the proportions of time spent (duty-cycle) and power consumptions during that time respectively in full and standby activity modes. The satellite terminal consumes $22W$ and $3.14W$ when it works in full and standby activity modes, respectively. This work considers a broadband satellite offering a throughput of $0.5Tbps$, capable of supporting maximum $227,000$ nodes. Considering this fact, it is pertinent to note that 0.1% of total duty-cycle allocated to a single node, should be enough to support the throughput needs reported in Figure 3. In this case, the satellite terminal needs to be in full activity mode only for 0.1% of the time and it would remain on standby mode for the rest of 99.9% duty-cycle. Then, by setting the duty-cycle in full activity mode to 0.1%, it is easy to realize that the power consumed by a satellite terminal is equal to $3.16W$ using Eq. (7).

Long-Range WiFi (standardized as IEEE 802.11ah) is another emerging backhaul capable technology operated in the sub-GHz band. This technology is intended to specifically target most of the future IoT and M2M scenarios. Despite very recent standardizations, it has already taken many breaths away and is being considered an effective milestone achieved by IEEE task group. It targets a significantly higher radio coverage than its predecessors on the cost of compromising on intermediary data rate; even then enough to serve the needs of many prospective LoRa applications. Hence, it may also be one of the candidates to support backhaul communication in combination with front-end LoRa. Thanks to the notion of Traffic Indication Map and Page Segmentation, extremely low power consumption is one of the major reasons to support Long-Range WiFi. The power consumption of Long-Range WiFi gateway can be approximated not more than $1.35W$ assuming full load and neglecting the slight power variation in circuitry differences [22], [23]. It is important to note that Long-Range WiFi offers significantly lower energy consumption but the radio coverage may vary up to a maximum of $1km$. To conclude, Table III presents some relevant parameters related to the proposed wireless technologies considered for the LoRaWAN backhaul.

TABLE III
IMPORTANT PARAMETERS EXHIBITING BACKHAUL CAPABILITIES FOR WIRELESS TECHNOLOGIES

Technology	**Data rate (Mbps)**	**Coverage (Km)**	**Spectrum**	P_{BH} **(W)**
LTE	0.5-28	5-50	Licensed	**5.10**
WiMAX	20-30	6-10	Lic. and Unlic.	**5.00**
Satellite	2.2-10	100-36000	Lic. and Unlic.	**3.16**
Long-Range WiFi	0.65-234	1	Unlicensed	**1.35**

Overall power consumption, P_{tot}

Despite being different with respect to throughput profiles demonstrated in Figure 3, the applications (requiring very low data rate) do not significantly influence the total power consumption. Therefore, for the scope of this work, the power profile related to the most energy-consuming application is taken into account. It is also assumed that the LoRa interface of a gateway is always-on, i.e., 24 hours/7 days. Furthermore, it works with its full potential (constantly listening on maximum number of supportable channels using all the LoRaWAN data rate options simultaneously), thus always registering an average power consumption as reported in the latest column of Table II.

In line with these premises, Figure 4 shows the resulting power demand against each LoRaWAN gateway vendor when choosing different backhaul technologies discussed above. Obtained results clearly demonstrate how does an LTE-based backhaul cause higher power consumption, which varies from $11.28W$ to $17.5W$ with respect to different LoRa vendors considered in the proposed analysis. At the same time, a WiMAX backhaul also depicts the consumption readings quite similar to LTE. Then, the power consumption of a satellite backhaul becomes moderate. But, it is evident how Long-Range WiFi exhibits the lower power consumption when compared to other backhaul solutions. In particular, its power consumption spans from $7.53W$ to $13.75W$, depending on different LoRa vendors. On the other hand, by focusing the attention on different LoRa vendors, it is possible to observe that, at the time of this writing, Multitech's Conduit provides the most energy-efficient LoRa gateway.

V. SIZING THE PHOTOVOLTAIC PLANT

Sizing the PV plant refers to evaluating the appropriate size of solar modules and storage batteries required to make the proposed cable-less LoRaWAN gateway always operational. It is done by addressing two main considerations. First, the

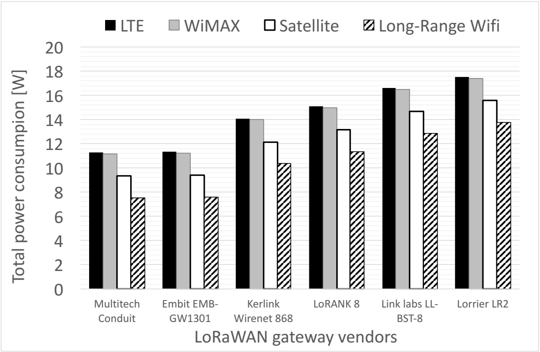


Fig. 4. Overall power consumption of a cable-less gateway, evaluated against different LoRa vendors and backhaul options

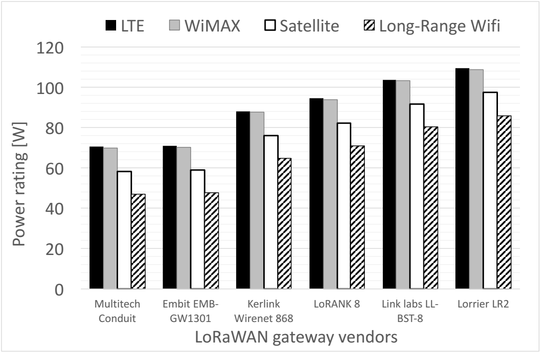


Fig. 5. Power rating of a PV plant, evaluated against different LoRa gateway vendors and backhaul options

size of a PV plant is evaluated based on power demand of the cable-less LoRaWAN gateway, the standard solar radiations in a specific geographical region, and the efficiency of the solar module based on its material. Second, sizing the batteries (storage rating) depends on the amount of energy required to feed the cable-less LoRaWAN gateway also during the cloudy days.

As PV plants endure incapability to harvest energy in the absence of sunlight, they must be sized to cater worst-case conditions. In particular, the size of PV plant and storage capacity should appropriately be evaluated to accommodate the energy harvested during seven consecutive sunny days of summer. This surplus energy accumulated on the storage can be utilized to filter out the fluctuations of energy availability in cloudy winter days. But, It solely depends on the weather conditions of a particular region. Here, we are considering a PV plant installed in the City of Bari, on the southern part of Italy. Taking into account the meteorological record of this region [24], the number of days with bad weather conditions ranges from two to seven in a month round the year. As a worst case scenario, there may be a possibility of seven consecutive days of bad weather per calendar month in a cloudy winter. Hence, the PV system is designed keeping in view the worst case conditions and is capable enough to compensate the energy demands during this period to make the cable-less LoRa gateways always operational.

A. Power rating of the PV plant

By assuming that the cable-less LoRaWAN gateway is always operational, the maximum amount of energy that an individual PV plant has to generate, i.e., P_{PV_rating}, depends upon the power requirement of a cable-less gateway, i.e., P_{tot}, the total number of hours available within a year, i.e., $H_{year} = 8,760$, and the insolation period defined as the number of hours in a year during which the PV plant is directly exposed to sun's radiations, i.e., H_{ins}. Therefore, P_{PV_rating} can be represented as:

$$P_{PV\_rating} = \frac{P_{tot}\, H_{year}}{H_{ins}}. \tag{8}$$

The value of P_{PV_rating} against different LoRa gateway vendors and backhaul wireless technologies is depicted in Figure 5. It is evaluated by setting $H_{ins} = 1400$, which represents the average insolation period for the Mediterranean countries (like the southern part of Italy) [25]. From Figure 5, it is possible to observe that P_{PV_rating} varies between $47.12W$ and $109.5W$, depending upon the chosen combinations of front-end chipsets and backhaul solutions. Moreover, as expected from Eq. (8), the higher the power requirement of a cable-less gateway, the higher the capability of a suitable PV plant. As already highlighted in Figure 4, the Multitech Conduit LoRa chipset, when employing with Long-Range WiFi as a backhaul, exhibits the minimum power requirement. Accordingly, it yields the lower bound of P_{PV_rating}. On the contrary, Lorrier LR2 registers the maximum power consumption when combined with LTE as a backhaul, thus achieving the upper bound of P_{PV_rating}.

B. Storage rating of the PV plant

Let the *production profile* be the amount of energy harvested, hour by hour, during the day. It is closely coupled with the environment where the plant is installed and its statistics would undergo abrupt variations for different regions. The location and orientation of solar panels is also important and may have significant impact on the expected output. For example, an array tilt would significantly affect the output up to 20% as compared to a flat surface. It has been observed that the tilt angle of 20 to 30 degree from the horizontal surface would yield the highest level of output in most of the regions. This effect goes on increasing from south to north regions moving away from the equator [26].

Just to provide an example, Figure 6 shows the production profile related to a PV plant working on a clear sunny day, as well as dimensioned for a cable-less LoRaWAN gateway that uses the Multitech Conduit chip as the front-end technology and LTE as the backhaul technology. From the Figure, it is possible to observe that production profile varies as a function of the time and reaches a peak value around midday. On the other hand, instead, the power demand, i.e., P_{tot}, remains the

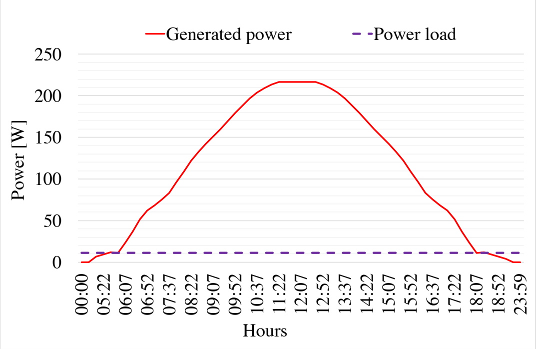


Fig. 6. Energy production profile of a PV plant against the load on a full summer day of south Italy

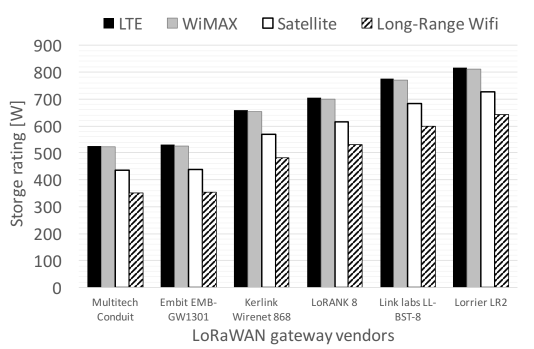


Fig. 7. Storage rating of a PV plant, evaluated against different LoRa gateway vendors and backhaul options

same throughout the day for each combination of vendor and chosen backhaul. Here, there is a clear possibility of saving the surplus amount of harvested energy during the daytime that can compensate the power demand at night time, as well as the amount of energy required to feed the cable-less LoRaWAN gateway on cloudy days when the consumption profile is higher than production. It is important to note that the appropriate size of storage rating also depends upon the actual weather conditions of a specific region. As per meteorological record for Bari, a city located in the south of Italy, the average number of days with precipitation, N_{BW}, ranges from two to seven in a calendar month [24]. Hence, the appropriate size of the storage can be obtained by considering an extreme weather condition characterized by seven consecutive days of precipitation(i.e. N_{BW} = 7) to support uninterrupted operation round the year. In other words, in order to make a cable-less LoRaWAN gateway operational also in these seven days, the storage must provide an amount of energy equal to $N_{BW} \cdot 24h \cdot P_{tot}$.

Now, let $\eta_{batt.}$ be the efficiency of the storage and $T_{discharge}$ be the total discharge time of the storage, then by assuming $\eta_{batt.} = 90\%$ and $T_{discharge} = 4$h for a lithium-ion battery [17], the storage rating can simply be expressed as:

$$P_{storage\_rating} = \frac{N_{BW} \cdot 24 \cdot P_{tot}}{4 \cdot 0.9}. \tag{9}$$

Results are reported in Figure 7. Also in this case, it is possible to remark the same considerations: the storage rating increases with the power need of a cable-less LoRaWAN gateway and the combination of Multitech Conduit chipset along with Long-Range WiFi backhaul is able to register the lowest battery size.

Furthermore, it should be clear that the storage rating can significantly be affected in case of different charge/discharge cycle. Similarly, considering other types of batteries (e.g. lithium-polymer battery or nickel-cadmium battery) would also affect the efficiency and charge/discharge cycle instead of a lithium-ion battery. Moreover, as per the physical constraint, the efficiency does not remain constant as the battery life goes on.

VI. COST-SAVING AND CARBON FOOTPRINT ANALYSIS

The aim of this Section is to highlight the socio-economic benefits derived from the deployment of cable-less LoRaWAN gateways.

A. *OPEX related to a conventional grid-powered LoRaWAN gateway*

Annual OPEX due to energy consumption is the first among overall costs that can be avoided by employing the proposed cable-less gateway architecture for public and private LoRaWAN infrastructure providers. Table IV shows the OPEX due to the energy consumption by a single gateway when connected to a power grid. It holds particular importance in case of large-scale deployments where hundreds (in some cases, thousands) of gateways may be deployed. Results demonstrate the annual costs and the costs after 10 years of activity, respectively, in two rightmost columns. In particular, OPEX is computed by considering the average electricity price for Italian industry, that is about 0.2 €/kWh [27].

TABLE IV
OPEX RELATED TO CONVENTIONAL GRID-POWERED LORAWAN GATEWAYS, EVALUATED AGAINST DIFFERENT VENDORS

LoRaWAN Gateway Vendors	**Yearly power demand [kW/h]**	**Yearly OPEX [€]**	**OPEX over 10 years [€]**
Multitech Conduit	54.13	**10.83**	**108.3**
Embit EMB-GW1301	54.75	**10.95**	**109.5**
Kerlink Wirenet 868	78.84	**15.77**	**157.7**
LoRANK 8	87.6	**16.81**	**168.1**
Links-lab LoRa	100.74	**20.15**	**201.5**
Lorrier LR2	108.97	**21.8**	**218.0**

B. *CAPEX related to a cable-less LoWaWAN gateway*

Power and storage ratings of a PV plant significantly influence installation costs. In Italy, the average cost of a lithium-ion battery together with PV plant is around 2,000 €/kW [28].

This value is taken into account for estimating the CAPEX needed to deploy a cable-less LoRaWAN gateway. Obtained results are shown in Figure 8. In general, installation costs of a PV plant for a cable-less LoRaWAN gateway ranges from 797 € to 1,852 €. In particular, the lowest costs can be achieved when the combination of Multitech Conduit chip is chosen as a front-end communication interface and the Long-Range WiFi is adopted for the backhaul link.

It is pertinent to note that the CAPEX is calculated for a PV system aiming to store ample energy to ensure an uninterrupted operation of LoRaWAN gateway keeping in view the seven consecutive days of bad weather conditions. Of course, it can significantly be reduced for shorter periods. In addition, this CAPEX can also be reduced by buying solar panels and battery cells of lower quality.

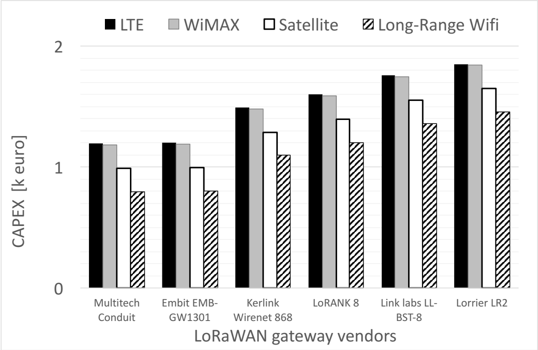


Fig. 8. CAPEX related to a PV plant feeding a cable-less LoRaWAN gateway, evaluated against different LoRa gateway vendors and backhaul options

C. Cost-saving analysis

From the network operator's point of view, cost-saving is one of the most significant metrics to calculate for evaluating the usefulness of the proposed architecture. Indeed, the analysis presented herein aims at demonstrating a set of conditions according to which the deployment of cable-less LoRaWAN architecture represents a suitable solution from the economic perspective. To this end, it is assumed that the lifetime of the LoRaWAN architecture is set to 10 years.

Let C^{Grid}_{CAPEX}, C^{Grid}_{OPEX}, C^{PV}_{CAPEX}, and C^{PV}_{land} be the capital costs required for setting up a grid connectivity, the operational costs related to the conventional grid-based LoRaWAN deployment and estimated over the period of 10 years, the capital cost incurred for the deployment of the proposed architecture (as reported in Figure 8), and the operational cost related to the land acquisition of a PV plant estimated over the period of 10 years, respectively. Thus, the cost-saving after the reference period of 10 years, i.e, CS, can be estimated as:

$$CS = C^{Grid}_{CAPEX} + C^{Grid}_{OPEX} - C^{PV}_{CAPEX} - C^{PV}_{land}. \tag{10}$$

All the common costs (i.e. actual investment in each gateway, site acquisition, and maintenance costs) have not been taken into account for this analysis, as they are the same in both the cases. Here, C^{Grid}_{OPEX} and C^{PV}_{CAPEX} are reported in Table IV and Figure 8, respectively. While, C^{PV}_{land} can be evaluated by taking into account the land needed to acquire for the installation of PV plant. According to [17], the land acquisition for PV plant, i.e., PV_{LA} can be calculated as:

$$PV_{LA} = \frac{P_{PV\_rating}}{\eta_{panel}\ SR_{standard}}, \tag{11}$$

where η_{panel} and $SR_{standard}$ are the average efficiency of the solar module and the standard solar radiations, respectively. Solar modules composed of different materials, exhibit different system efficiencies. Here, polycrystalline silicon material has been considered, which undergoes $\eta_{panel} = 14\%$ and the standard solar radiations value is set as $SR_{standard} = 1kW/m^2$, that is the typical value for the southern part of Italy [25]. The computed land acquisition values are reported in Figure 9. As expected, the higher the P_{PV_rating}, the higher the computed land acquisition. However, the results in Figure 9 also demonstrate that the land acquisition is always lower than $1m^2$, which ensures a good space saving. Accordingly, the cost-saving analysis discussed herein simply assumes that $C^{PV}_{land} = 0$.

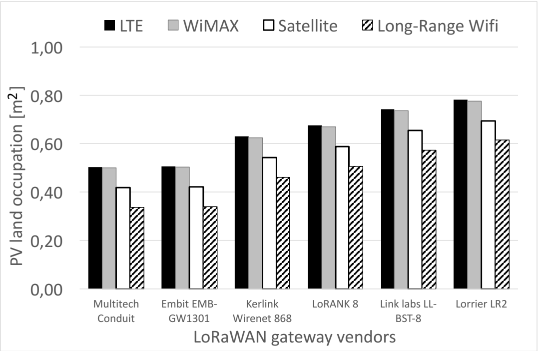
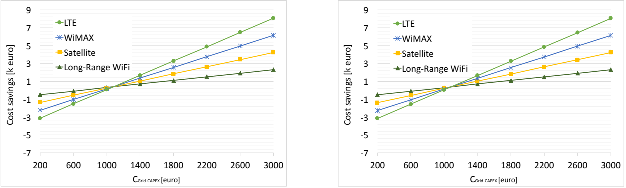
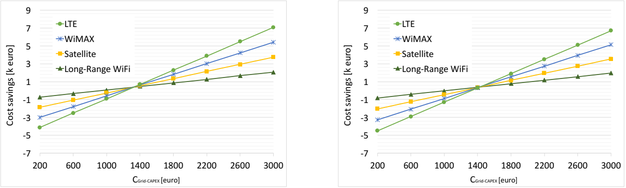


Fig. 9. Land acquisition needed for different LoRa gateway vendors with multiple backhaul options

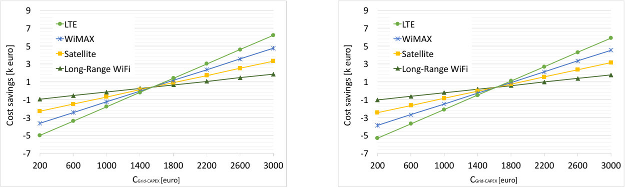
Figure 10 reports the cost-saving calculated, for all the combination of front-end and backhaul wireless links, as a function of C^{Grid}_{CAPEX}. It is evident that the higher the installation costs of LoRaWAN gateway due to grid connectivity, the higher the economic benefits gained by the proposed cable-less architecture. Nevertheless, in order to better evaluate the actual return on investment for this kind of infrastructure, it should be noted that network operators would be able to achieve their break-even when C^{Grid}_{CAPEX} is equal to the value reported in Table V. In particular, Table V indicates the specific values of C^{Grid}_{CAPEX} for which the curves reported in Figure 10 intersect at the x-axis. The results should be interpreted as follows: in case the costs required for attaching a LoRaWAN gateway to the grid are higher than those reported in Table V, network operators are able to achieve an instant profit throughout the lifetime of the deployed system. In addition, when the observation period is set to 10 years, the resulting economical gain is shown in Figure 10. Anyway, in line with all the considerations previously reported, it is possible to finally remark that the cable-less LoRaWAN gateway, leveraging the combination of Multitech Conduit as a front-end communication interface and the Long-Range WiFi adopted for the backhaul link, is the most economically-efficient solution.



(a) Multitech Conduit (b) Embit EMB-GW1301



(c) Kerlink Wirenet 868 (d) LoRANK 8



(e) Link labs LL-BST-8 (f) Lorrier LR2

Fig. 10. Cost-saving analysis as a function of C_{CAPEX}^{Grid}

TABLE V
BREAK-EVEN POINTS OF DIFFERENT LORA GATEWAYS AGAINST BACKHAUL TECHNOLOGIES (K€)

LoRaWAN Gateway Vendors	LTE	WiMAX	Satellite	Long-Range WiFi
Multitech Conduit	1.09	1.08	1.08	0.69
Embit EMB-GW1301	1.10	1.09	1.09	0.70
Kerlink Wirenet 868	1.34	1.34	1.33	0.94
LoRANK 8	1.44	1.42	1.42	1.04
Link labs LL-BST-8	1.16	1.15	1.15	1.16
Lorrier LR2	1.64	1.63	1.63	1.24

D. Carbon footprint analysis

Green networks are aimed at reducing a proportion of CO_2 that is continuously polluting our environment due to ICT infrastructures. Each kWh of electricity generated and provided by the direct grid, CO_2^{Grid}, roughly produces $386g$ of carbon, as per the latest statistics by International Energy Agency [29]. The generation of a PV system also involves carbon emissions. But, supposing to distribute these CO_2 emissions among the lifetime of the system, it is possible to consider an equivalent amount of carbon emissions associated with a cable-less LoRaWAN gateway, CO_2^{PV}, equal to $20g/kWh$ as compared to $386g/kWh$ in case of direct grid connectivity [30]. By multiplying both the above quantities with the annual energy consumption of a single gateway, ($E_{year} = 24 \cdot 7 \cdot P_{tot}$, where P_{tot} is the peak power consumption as reported in Figure 4), gives an estimation of the difference in annual carbon emission of both the cases using equation 12.

$$CO_2^{savings} = (CO_2^{Grid} \cdot E_{year}) - (CO_2^{PV} \cdot E_{year}) \tag{12}$$

Having this in mind, the actual CO_2 saving is calculated by subtracting the amount of equivalent carbon emission per annum related to the PV plant from the one characterizing the conventional grid-powered approach, as depicted in Figure 11. The proposed cable-less solution is able to ensure a yearly CO_2 saving ranging from $24kg$ to $56kg$ for a single gateway. These encouraging statistics may lead towards tons of savings of carbon emission annually, when the proposed approach is applied on large-scale deployments. As a consequence, the cable-less option may prove to be of great value for network operators towards the deployment of next-generation green IoT infrastructures.

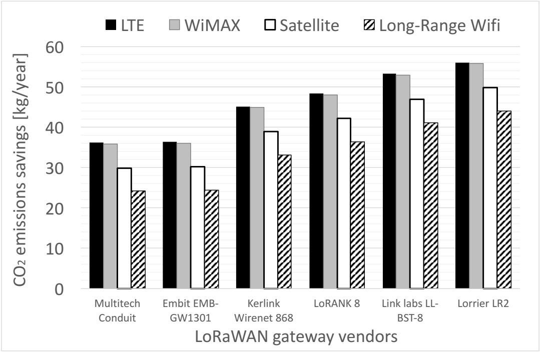


Fig. 11. CO_2 savings of cable-less gateway against multiple backhaul options

VII. CONCLUSION AND FUTURE ACTIVITIES

This work proposed a cable-less Long Range Wide Area Network architecture, where the gateway is powered by an energy harvesting source and is connected to the rest of the network through a wireless backhaul link. The resulting architecture not only induces ease and scalability when compared to conventional design constraints, but it also provides a cost-effective and environment-friendly way enabling rapid LoRaWAN deployments, towards green communication models. The proposed energy harvesting gateway model, however, introduces some new research issues to be tackled alongside the conventional challenges of radio access networks (like resource allocation, interference, and mobility management). In general, almost every kind of Renewable Energy Sources are prone to unpredictable behavior that causes a variable amount of energy scavenging depending upon various factors. Hence, only introducing the notion of Renewable Energy Sources is never enough without proper considerations of network management techniques. It is not only significant to minimize the energy consumption but also towards achieving energy sustainability by defining a new set of algorithms, protocols, and procedures targeting Quality of Service requirements keeping in view the amount of harvested energy in hand. The network should be smart enough to dynamically respond towards the fluctuating energy conditions on the storage. Although, dealing with these issues is out of the scope of this work but they deserve an active attention by the research community working on energy harvested wireless systems in the future.

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